Multi-GNSS Working Group Technical Report 2019

P. Steigenberger[1], O. Montenbruck[1]

[1] Deutsches Zentrum für Luft- und Raumfahrt (DLR)
German Space Operations Center (GSOC)
Münchener Straße 20
82234 Weßling, Germany
E-mail: peter.steigenberger@dlr.de

1 Introduction

The Multi-GNSS Pilot Project (MGEX) is the main activity of the IGS Multi-GNSS Working Group (MGWG). The membership of the MGWG has not changed in 2019. Altogether 13 GNSS satellites as well as a GNSS augmentation payload onboard a host satellite have been launched in 2019. The evolving systems Galileo and BeiDou are close to full operational capability and the renewal of the GPS and GLONASS constellation continues.

2 GNSS Evolution

The GNSS satellites launched in 2019 are listed in Table 1. In January 2019, the first GPS III satellite started signal transmission including the new civil L1C signal (Thoelert et al. 2019). The second GPS III satellite nicknamed Magellan was launched in August 2019 but has not yet started signal transmission within the PRN range trackable by commercial geodetic GPS receivers (G01 – G32). For all healthy Block IIR-M and IIF satellites, flex power operations (Steigenberger et al. 2019b) were observed on June 20 and 21, 2019. The most obvious effect was an increase of the carrier-to-noise density ratio of the P(Y)-code tracking by roughly 10 dB.

In 2019, two satellites of the GLONASS constellation (R723/R12 and later R10; R733/R06) suffered from single-frequency transmission on L1 only. The lack of L2 observations prohibits the precise orbit and clock determination of these satellites. Transmission outages of several weeks occurred for the GLONASS PRNs R04, R10, and R24 resulting in an

Table 1: GNSS satellite launches in 2019.

Date	Satellite	Type
20 Apr 2019	BeiDou-3 IGSO-1	IGSO
17 May 2019	BeiDou-2 GEO-8	GEO
27 May 2019	GLONASS-M+	MEO
24 Jun 2019	BeiDou-3 IGSO-2	IGSO
22 Aug 2019	GPS III-2	MEO
22 Sep 2019	BeiDou-3 MEO-23 and MEO-24	MEO
09 Oct 2019	EUTELSAT 5 West B (EGNOS)	GEO
04 Nov 2019	BeiDou-3 IGSO-3	IGSO
23 Nov 2019	BeiDou-3 MEO-21 and MEO-22	MEO
11 Dec 2019	GLONASS-M+	MEO
16 Dec 2019	BeiDou-3 MEO-19 and MEO-20	MEO

incomplete GLONASS constellation of less than 24 healthy satellites. R723/R12 and R742/R04 were replaced by the newly launched GLONASS-M+ satellites R858 and R859 in June and December 2019, respectively. Despite its single-frequency limitation, R723 continued signal transmission with PRN R10. Further GLONASS launches including the last GLONASS-M satellite as well as GLONASS-K1 and -K2 satellites are planned for 2020.

With the launch of three IGSO and six MEO satellites, BeiDou made a large step towards

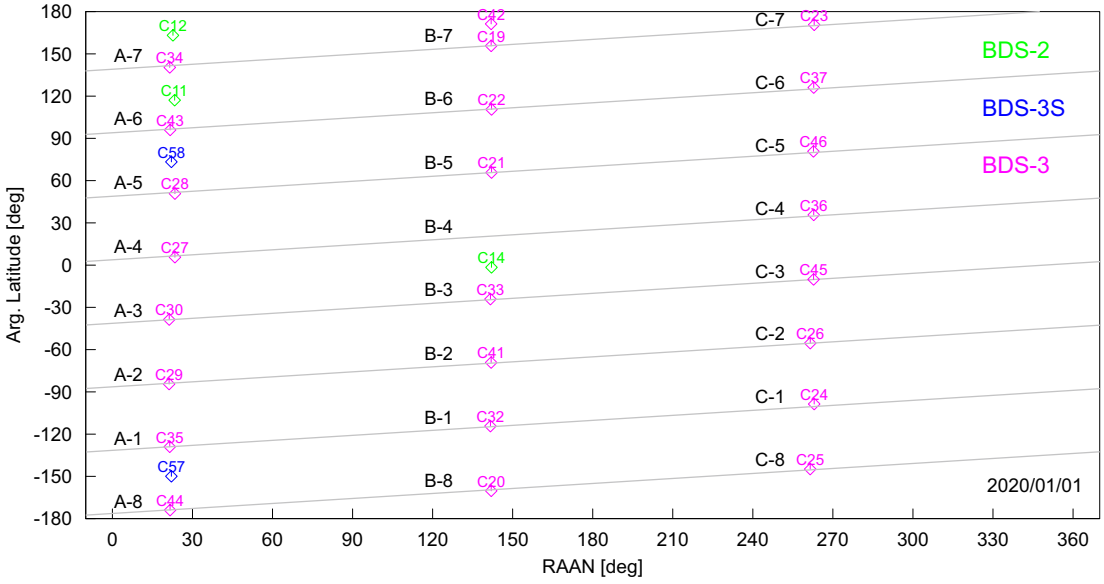

Figure 1: Constellation of BeiDou MEO satellites as of January 2020. C42 is drifting to its designated slot B-4.

the completion of the BDS-3 constellation. Whereas the nominal number of 24 MEO and three IGSO satellites has already been reached by the end of 2019, two GEO launches are expected for 2020. Figure 1 shows the constellation of BDS-2, BDS-3S, and BDS-3 MEO satellites as of January 2020. As orbital plane A is already fully populated with BDS-3 MEO satellites, two BDS-2 MEO satellites (C11 and C12) and two BDS-3S MEO satellites (C57 and C58) are placed in between the official orbital slots. The same is true for the BDS-2 satellite C14 in orbital plane B.

EUTELSAT 5 West B, located at 5° West, is a communication satellite hosting a payload for the European Geostationary Navigation Overlay System (EGNOS). The spacecraft suffers from an incident on one of the two solar panels (EUTELSAT 2019) but the impact on the EGNOS payload is currently unknown.

Version 3.0 of the BeiDou B1I interface control document (ICD) was published in February 2019 (China Satellite Navigation Office 2019). Compared to the previous version 2.1, of the B1I+B2I ICD, it defines the full range of BeiDou PRNs (up to 63) including the allocation of 10 PRN numbers for geostationary satellites and defines an updated scheme for transmission of the full BDS-2/3 constellation almanac. Furthermore, it introduces the BeiDou Coordinate System (BDCS) as a replacement for the earlier China Geodetic Coordinate System 2000 (CGCS2000) and defines a tighter synchronization (50 vs. 100 ns) of BeiDou System Time (BDT) with UTC. In December 2019, beta versions of the ICDs for the B2b open service signal of BeiDou-3 (CSNO 2019d) as well as the precise point positioning service (CSNO 2019e) were made available by the Chinese Satellite Navigation Office.

As an addition to the Galileo Open Service ICD, the European Union published a technical note on the E6-B/C Codes (European Union 2019a). It contains the primary and secondary codes for the E6-B and E6-C signals fostering the development of E6-capable Galileo receivers. In July 2019, Galileo suffered from a six-day service interruption. Whereas all satellites continued to transmit proper navigation signals, no broadcast ephemerides were transmitted during this time period (European Union 2019b). Most of the MGEX ACs were not affected by this issue and continued to provide high-quality Galileo orbit and clock products. The incident was analyzed by an independent inquiry board. Its recommendations are given in European Commission (2019).

For QZSS, three ICDs were updated in December 2019 (IS-QZSS-L1S-004 2019; IS-QZSS-L6-002 2019; IS-QZSS-TV-003 2019), amongst others to pave the way for the launch of the QZS-1 replacement satellite in 2020 as well as the extension to a 7-satellite constellation in 2023.

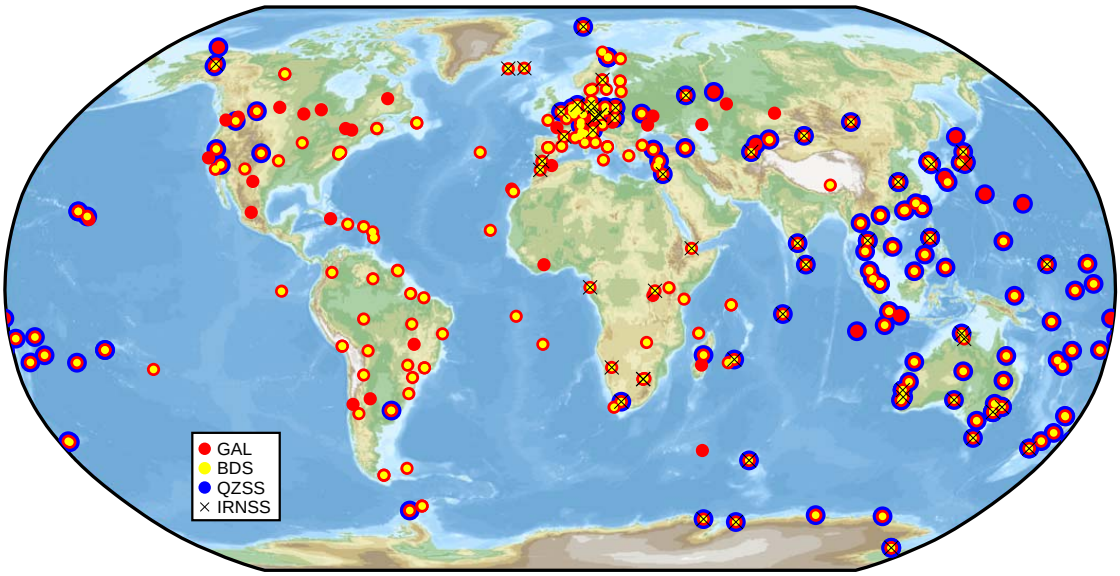

Figure 2: Distribution of IGS multi-GNSS stations supporting tracking of Galileo (red), BeiDou (yellow), QZSS (blue), and IRNSS (black crosses) as of January 2020.

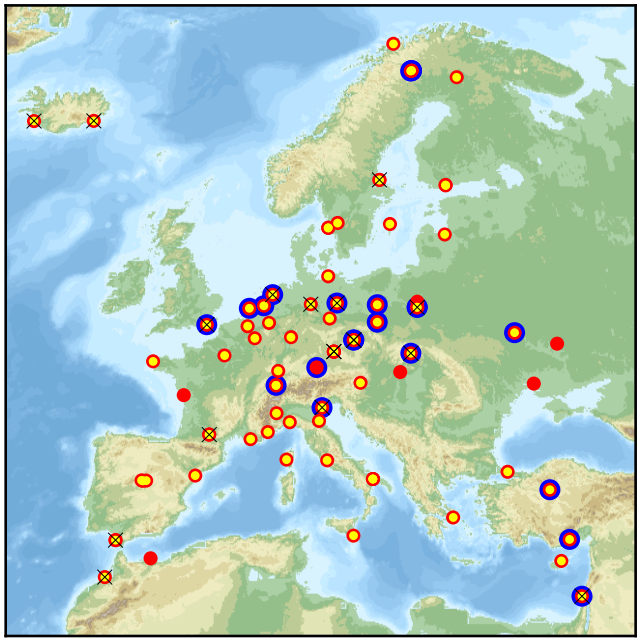

Figure 3: Distribution of IGS multi-GNSS stations in the European region as of January 2020.

Table 2: BeiDou-3 tracking capabilities of selected receivers and firmware versions. (x) indicates observables not supported by the receiver-internal RINEX converter. The second column indicates the second and third character of the RINEX 3 observation type (IGS RWG and RTCM, 2018).

Receiver		Javad TRE_3	Septentrio PolaRx 5	Trimble NetR9	Trimble Alloy
Firmware		3.7.6	5.3.0	5.42	5.42
PRN range		C01 – C37	C01 – C37	C01 – C37	C01 – C63
B1C	1P		(x)		
	1X	x			(x)
B1I	2I	x	x	x	x
B2a	5P		(x)		
	5X	x			(x)
B3I	6I	x	x	x	x
B2b	7Z	x			
B2ab	8X	x			

3 Network

As of January 2020, the IGS multi-GNSS tracking network comprises 309 stations, see Fig. 2 and 3. However, nine of these stations did not provide any RINEX 3 observation data in 2019. For seven stations in New Zealand and Antarctica operated by GNS Science (AUCK00NZL, CHTI00NZL, DUND00NZL, MQZG00NZL, SCTB00ATA, WARK00NZL, WGTN00NZL), the provision of RINEX 3 files was stopped in January 2019 due to changes in the data generation chain (IGSSTATION-7581). In late 2019, the station category 'MGEX experimental' was changed to 'IGS experimental'. As of December 2019, five stations belong to this category.

GLONASS-M+ satellites are capable of transmitting a CDMA signal on the L3 frequency. However, these signals are not fully compliant with the corresponding ICD (Sleewaegen 2020), neither the current version (Russian Space Systems 2016), nor an earlier version as stated in Urlichich et al. (2019). Several receiver manufacturers have adopted their receiver firmware in order to offer L3 capabilities for individual satellites. However, as of late 2019, very few receivers in the IGS network provide a comprehensive tracking of the most recent GLONASS-M+ satellite R859/R04.

BeiDou-3 tracking capabilities of the IGS multi-GNSS network were significantly enhanced in 2019, primarily due to receiver firmware updates but also due to receiver replacements. An overview of the BeiDou-3 signal tracking of selected receivers and firmware versions is given in Table 2. Starting with firmware version 5.42 released in August 2019, the Trimble Alloy receiver is capable of tracking BeiDou-3 PRNs up to C63. Javad released firmware 3.7.8 on December 26, 2019, supporting also PRNs up to C63 for the newest generations of Javad receivers and up to C46 for older generations. However, none of the IGS receivers utilizes this firmware as of early January 2020. Other receivers are currently limited to

the BeiDou PRN range C01 – C37.

Along with the introduction of new BeiDou signals and the definition of associated RINEX observation codes, various inconsistencies in vendor or user generated RINEX observations files could be noted in the IGS data repository. RINEX files of Javad receivers with version $\leq$ 2.0.157 of the data conversion software `jps2rin` erroneously report BeiDou-3 B1C data+pilot observations (`1X`) as RINEX code `2X`. BeiDou-3 `2X` observation codes are also generated by a translation bug of the `gfzrnx` software prior to version 1.12-7747 (IGSSTATION-7849).

BeiDou-2 and BeiDou-3 satellites transmit different signals in the B2b band (1207.14 MHz). Whereas BeiDou-2 utilizes a BPSK(2) signal for the open service on the I-channel (RINEX code `7I`), the in-phase component of a QPSK(10) signal is used for the BeiDou-3 B2b open service (CSNO 2019d). Currently, BeiDou-3 B2b observations are obtained by Javad TRE_3 receivers in the IGS network based on combined tracking of the I- and Q-channel (RINEX code `7Z`). However, numerous RINEX files of Javad receivers contain `7I` observations for BeiDou-3 instead of `7Z` due to outdated conversion software (`jps2rin` 2.0.168 and 2.0.170; version 2.0.187 correctly reports `7Z` for BeiDou-3).

Currently, the BeiDou-3 `1P` and `5P` observables are not supported by the PolaRx5 receiver built-in RINEX converter, but can be generated with Septentrio's external conversion software `sbf2rin` version 13.4.3. The QZSS L1Sb SBAS signal of the geostationary QZS-3 satellite can be tracked by Javad TRE_3 receivers but no RINEX observation code has been defined for this signal so far.

Another problem encountered along with the rapid deployment of new GNSS satellites and signals is the limited number of tracking channels available in various stations with first-generation multi-GNSS receivers. As a result, some IGS stations provide only intermittent tracking of individual Galileo and/or BeiDou satellites. Unless those receivers can be replaced by more modern units, station-specific tracking schemes need to be developed to obtain a reasonable tracking coverage in accord with existing hardware limitations.

4 Products

The analysis centers contributing products to MGEX are listed in Table 3. Updates and changes of the MGEX orbit and clock products include:

- Inclusion of BeiDou-3 in the orbit and clock products of WU starting with day of year 1/2019.
- Long filenames: WU since 1/2019; GFZ rapid products since GPS week 2038 (27/2019, IGSMAIL-7748); TUM since 89/2019.
- Improved Galileo ambiguity resolution for CNES/CLS product since February 3, 2019 (Perosanz et al. 2019).
- Hourly orbit and clock product from Wuhan University available since 65/2019.

Table 3: Analysis centers contributing to IGS MGEX.

Institution	Abbr.	GNSS
CNES/CLS	GRGOMGXFIN	GPS+GLO+GAL
CODE	CODOMGXFIN	GPS+GLO+GAL+BDS2+QZS
GFZ	GFZOMGXRAP	GPS+GLO+GAL+BDS2+QZS
JAXA	JAXOMGXRAP	GPS+GLO+QZS
SHAO	SHAOMGXRAP	GPS+GLO+GAL+BDS2
TUM	TUMOMGXRAP	GAL+BDS2+QZS
Wuhan University	WUMOMGXFIN	GPS+GLO+GAL+BDS2+BDS3+QZS
	WUMOMGXULA	GPS+GLO+GAL+BDS2+BDS3

- Empirical thermal radiation model for Galileo satellites in CODE product since summer 2019 (Prange et al. 2019).
- Transition from conventional PCOs for BeiDou-2 to averaged estimated PCOs and inclusion of BeiDou-3 block-specific manufacturer PCOs in `igs14.atx` (GPS week 2056, IGSMAIL-7782).
- PCO and PCVs provided by GSA for the eight most recent Galileo satellites added to `igs14.atx` (GPS week 2060, IGSMAIL-7792).
- PCOs for the BeiDou-3 IGSO satellites added to `igs14.atx` (GPS week 2076, IGSMAIL-7843).

Since September 23, 2019, Galileo is also included in the CODE operational rapid and ultra-rapid orbit and clock products (IGSMAIL-7832).

Steigenberger and Montenbruck (2019) assessed the consistency of the MGEX orbit and clock products for the first term of 2018. They found a clock consistency of 2 cm for GPS, 5 cm for Galileo and GLONASS, and 10 cm for BeiDou-2. The mean combined orbit and clock consistency evaluated by the 95th percentile of the signal-in-space ranging error (SISRE) is 2 cm for GPS, 8 cm for GLONASS, 6 cm for Galileo, and 14 cm for BeiDou-2. More recent analysis of the December 2019 MGEX orbits and clocks gives a similar value for GPS and GLONASS but a significantly improved consistency of 4 cm for Galileo.

A prototype for an MGEX final orbit combination was developed by Geoscience Australia. Details on these activities are given in the ACC section of this report.

Multi-GNSS differential code bias (DCB) products are generated by CAS (daily rapid product) and DLR (quarterly final product). In the DLR product, additional BeiDou-3 DCB types were included as soon as a sufficient number of IGS receivers provided these observations:

- B1-2(I)/B2a(Data+Pilot), RINEX code `C2I-C5X`, January 2019
- B1-2(I)/B1(Data+Pilot), RINEX code `C2I-C1X`, March 2019
- B1-2(I)/B2b(Data+Pilot), RINEX code `C2I-C7Z`, August 2019

The CAS product includes additional BeiDou-3 DCBs currently not accessible with the

IGS network due to lacking tracking data (`C1D-C5D` and `C1D-C6I`) or sparse tracking data (`C1P-C5P`, `C1P-C6I`, `C1X-C8X`).

DLR's broadcast ephemerides product is provided with long filenames (prefix `BRDM00DLR`) starting with November 25, 2019 (day of year 329/2019). The same applies for the CNAV product with prefix `BRDX00DLR`. Both files are available in the default data directories of the IGS data centers. The provision of the products with short filenames (`brdm`/`brdx`) in the dedicated MGEX data directories will be stopped in the first months of 2020.

5 Satellite Metadata

Several new satellite metadata were published in 2019. Lockheed Martin released satellite antenna phase center offsets, group delay, and inter-signal corrections for GPS III SV01 (Lockheed Martin 2019). The Cabinet Office published additional metadata for the QZSS satellites:

QZS-1: optical properties for all surfaces; approximated shape of the L-ANT antenna cover (Cabinet Office 2019a)
QZS-2: approximated shape of the L-ANT antenna cover (Cabinet Office 2019b)
QZS-3: dimensions and optical properties of a reflector antenna on the −X side of the satellite (Cabinet Office 2019c)
QZS-4: approximated shape of the L-ANT antenna cover (Cabinet Office 2019d)

The European GNSS Agency made available mass, center of mass, antenna reference point location, antenna phase center offsets, and laser retroreflector offsets for the latest eight Galileo FOC satellites in April 2019 (GSA 2019). Corresponding antenna phase center variations were published in June 2019.

Satellite metadata for BeiDou-2 and BeiDou-3 were released by the Chinese Satellite Navigation Office (CSNO) in December 2019 (CSNO 2019a, b). This dataset includes PRN/SVN assignment, frequency-specific satellite antenna phase center offsets, mass, SLR retroreflector offsets, as well as areas and absorption coefficients (specular and diffuse reflection coefficients are missing). Additional information, attitude law, and file format descriptions are given in CSNO (2019c).

DLR measured the transmit power of recently launched GLONASS satellites with its 30 m high-gain antenna (Steigenberger et al. 2019a). For the GPS III satellites, a total transmit power of 300 W is assumed based on the measured Block IIF transmit power, the additional L1C signal, and slightly increased power levels for other signals.

The impact of metadata on Galileo and QZSS orbit determination is discussed in Li et al. (2019). As an example, a box-wing model based on the areas and optical properties could improve the orbit quality by up to 14 % in terms of 3D overlap RMS.

The MGWG maintains a metadata SINEX file covering most of the published metadata.

In particular, the MGEX satellite metadata file provides

- Time-dependent PRN and frequency channel assignments
- Satellite mass and center-of-mass location
- Equipment positions (antennas, LRAs)
- Transmit power

along with detailed references of the respective data sources. The latest version of this file is available at http://mgex.igs.org/igs_metadata.snx along with a format description. The file is intended as a centralized and standardized source of satellite metadata information for MGEX analysis centers and GNSS users. Extensions to cover additional parameters, e.g. box-wing models, are under discussion. In addition, the MGWG continues its effort to promote the release of further metadata by GNSS manufacturers and providers.

Acronyms

CAS Chinese Academy of Sciences
CLS Collecte Localisation Satellites
CNES Centre National d'Etudes Spatiales
CODE Center for Orbit Determination in Europe
DLR Deutsches Zentrum für Luft- und Raumfahrt
GFZ Deutsches GeoForschungsZentrum
JAXA Japan Aerospace Exploration Agency
SHAO Shanghai Observatory
TUM Technische Universität München
WU Wuhan University

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